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EFFECTS OF THE CHANGING COMPOSITION OF U.S. MANUFACTURING PRODUCTION ON ENERGY DEMAND

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by

G. Boyd, J.F. McDonald,* M. Ross,‡ and D.A. Hanson

Energy and Environmental Systems Division

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1 INTRODUCTION

The demand for energy is normally broken down by five principal sectors: industry, utilities, the residential sector, the commercial sector, and transportation. Industry is the most heterogeneous of these categories; the U.S. Department of Energy (DOE) includes agriculture, mining, construction, and manufacturing in the industrial sector for energy demand analyses. Manufacturing accounts for about 80% of total industrial energy demand and is itself a very heterogeneous collection of production activities. There were 448 manufacturing sectors as of 1972, as defined by the Standard Industrial Classification (SIC) method of the U.S. Department of Commerce. This diversity within manufacturing has hampered research efforts to formulate a manageable, yet convincing, model of manufacturing energy demand for explaining historical data and making projections.

The development of economic science in many applied fields such as energy economics typically proceeds through four stages:

1. Accumulation of data pertinent to the field of study,

2. Examination of these data to determine the salient facts that require formal "explanation" through economic models,

3. Formulation and empirical testing of economic models capable of accounting for the salient facts, and

4. Use of the models for forecasting and policy analysis.

While research is underway at all four stages to examine the demand for energy in manufacturing, our view is that much of this research is (and ought to be) focused on stage 2. Although some of the data collected (in stage 1) are inadequate, as documented by Ross,[1] sufficient data are certainly available to determine the basic facts of manufacturing energy demand. This report addresses the following questions:

1. What are the key results of research efforts to date to determine the salient facts of manufacturing energy demand?

2. How can these key results be summarized and simplified so that economic modeling (which is always a simplification of reality) is both feasible and useful?

3. Can our summary of key results help in formulating forecasts (preliminary forecasts) of manufacturing energy demand?

The report focuses on two key components or indicators of trends in manufacturing energy demand: (1) changes in *real energy intensity*, i.e., in the amount of energy used per unit of manufacturing output (e.g., the amount of electricity or fuel used per ton of steel or dollar of equipment produced), and (2) *sectoral shift*, i.e., changes in the mix of industrial output from energy-intensive to nonenergy-intensive sectors. Change in *aggregate energy intensity*, the ratio of total energy use to total manufacturing production, is the sum of the growth rates in these two indicators. A historical analysis has been carried out to identify these indicators separately for fuels and electricity. A similar analysis has been performed for a series of macroeconomic projections produced by the Wharton School of Economics.*

In a comprehensive study of energy demand in manufacturing, Marlay[2] summarized his results as follows:

> A major finding of this work is that the large and apparent gains in industrial energy efficiency after 1970 are primarily the result of two distinct phenomena. The first is a large reduction in energy demand caused by an unprecedented shift in the structure of industrial production away from energy intensive industries. The second is an accelerated gain in fossil fuel energy productivity. After 1970, both phenomena appear to have had nearly coequal energy reducing effects upon the whole. Hence, aside from efficiency improvements in industrial processes, the changing structure of industrial production was found to be an important determinant of industrial energy demand. It should be addressed explicitly in future theoretical treatments.

While Marlay's research is discussed in more detail in Sec. 2, it is worth noting at this point that he examined all 413 manufacturing sectors (as of the 1967 SIC manual) separately. A key objective of the research for this report was to determine whether the shift in the mix of manufacturing production can be captured by a simpler empirical analysis. How detailed does an economic model need to be to capture the sectoral shift (product mix change) effect on energy demand? In our view, the answer to this question is crucial because economic models capable of producing medium- and long-term forecasts must be reasonably simple in terms of the input variables required and the number of parameters that need to be estimated. Furthermore, it is our view that existing engineering models of manufacturing energy demand may have difficulty in capturing sectoral shift.

The discussion of sectoral shift in the subsequent sections of this report presents our preliminary results on the following issues: (1) the level of the economy at which

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*These projections have been used by the Energy Modeling Forum (EMF) to drive the models used in its eighth study, *Industrial Energy Demand, Conservation, and Interfuel Substitution under Alternative Energy Futures* (referred to as the EMF-8 study).

sectoral change has occurred, (2) the differences in the effect of sectoral shift on fuel and electricity intensity, (3) the differences in sectoral shift trends before and after the 1974 oil embargo by the Organization of Petroleum-Exporting Countries (OPEC), and (4) some causes of sectoral change.

2 REVIEW OF SELECTED STUDIES

This section reviews the most important studies of the sectoral shift phenomenon as it pertains to manufacturing energy demand, and in so doing introduces the basic notions used in research on the topic. Section 2.6 contains a brief summary and the conclusions of this review.

2.1 MYERS AND NAKAMURA

A 1978 study of the "sectoral shift" hypothesis -- i.e., that a significant portion of the reduction in aggregate energy intensity is due to sectoral shift -- was conducted by Myers and Nakamura.[3] They examined data from the *Census of Manufactures* for constant-dollar value added (using a gross national product [GNP] deflator) and purchased energy in manufacturing for 1967 and 1974-76. They disaggregated the manufacturing sector into two components: (1) the eight four-digit SIC industries that are the largest energy users and (2) the rest of manufacturing. These eight, which consisted of two paper industries, two chemical industries, and petroleum refining, hydraulic cement, basic steel, and primary aluminum, accounted for about 47% of purchased energy in manufacturing in 1976. The data obtained by Myers and Nakamura are summarized in Table 1.

Given this disaggregation of manufacturing into two sectors, the effect of sectoral shift on energy demand can be separated from that of improvements in energy efficiency as follows. Energy intensity (EI) in manufacturing can be defined as

$$EI = S_1 ei_1 + S_2 ei_2 \tag{1}$$

where:

S_1 (or S_2) = share of value added in manufacturing sector 1 (or 2), and

ei_1 (or ei_2) = the ratio of energy use to value added in manufacturing sector 1 (or 2).

For example, using the values for 1967 in Table 1,

$$EI = (0.1037)(199.436) + (0.8963)(25.515)$$

$$= 43.549.$$

The percentage change in EI can be written as

$$\frac{dEI}{EI} = \frac{\sum_{i=1}^{2} ei_i dS_i}{EI} + \frac{\sum_{i=1}^{2} S_i dei_i}{EI} \tag{2}$$

TABLE 1 Energy Use and Output in Manufacturing, 1967-1976[a]

Disaggregation Level, Year	Purchased Energy (10^{12} Btu)	Value Added (10^9 \$)[b]	Ratio of Energy Use to Output (10^3 Btu/\$)[b]
All manufacturing			
1967	15,649	359.34	43.5
1974	18,113	452.48	40.0
1975	16,668	406.67	41.0
1976	17,353	452.83	38.3
Eight energy-intensive industries			
1967	7,431	37.26	199.4
1974	8,592	47.81	179.7
1975	7,699	41.77	184.3
1976	8,103	46.25	175.2
Rest of manufacturing			
1967	8,218	322.08	25.5
1974	9,521	404.67	23.5
1975	8,969	364.90	24.6
1976	9,250	406.58	22.8

[a]Source: Ref. 3.

[b]In 1974 dollars.

where the first term is the sectoral shift effect and the second term is the efficiency effect.

The data obtained by Myers and Nakamura in Table 1 show that a 10.83% decline in energy intensity occurred from 1967 to 1976 (from 43.5 to 38.3 x 10^3 Btu/\$). Very little of this decline can be accounted for by a relative shift away from the eight industries with high energy intensities. Of the total value added in manufacturing, these eight industries accounted for 10.37% in 1967 and 10.21% in 1976. Of that 10.83% decline in energy intensity from 1967 to 1976, only 0.62% can be attributed to the change in output mix, as measured by Myers and Nakamura. The remaining 10.21% reflects general efficiency improvements in the use of energy and/or changes in output mix within the *rest* of manufacturing. On the other hand, for the years immediately after the oil embargo, 1974 to 1976, a 4.25% decline occurred in aggregate energy intensity, of which 1.35% can be attributed to the sectoral shift effect. This is about 32% of the decline in energy intensity in total manufacturing.

2.2 SAMUELS ET AL.

A more recent study of shifts in product mix versus changes in energy intensity as determinants of energy consumption in manufacturing was conducted by Samuels et al.[4] Their study covered the period 1975 to 1980. They decomposed the manufacturing sector into the 448 four-digit SIC industries. Purchased fuels and electricity data were obtained from the U.S. Bureau of the Census, *Annual Survey of Manufactures*, and output was measured by the value of shipments (gross output) in 1972 dollars. The total reduction in energy used per dollar of shipments from 1975 to 1980 was decomposed into (1) the reduction brought about by shifts away from energy-intensive sectors and (2) the reduction due to improvements in energy efficiency. The authors' use of four-digit SIC industries makes their level of disaggregation correspond to that used by Marlay.[2]

The study showed that most of the change in energy intensity (energy used per dollar of shipments) from 1975 to 1980 was due to improvements in energy efficiency and not to changes in product mix.* Table 2 summarizes the study's results. Product mix changes account for 23.4% of the reduction in total energy intensity and only 8.1% of the reduction in electricity intensity. The authors state that these results are consistent with those obtained by Marlay, who used a more complex approach in terms of data sources and data manipulation.

TABLE 2 Reductions in Energy Intensity in the Manufacturing Sector, 1975-1980 (%)

Reason for Reduction	Total Energy	Fuels	Electricity
Efficiency improvements	14.4	15.8	7.9
Product mix changes	4.4	5.1	0.7
Total	18.8	20.9	8.6

Source: Ref. 4.

*A potential problem with this study is that 1975 was a recession year. The data shown in Table 1 indicate that 1975 is out of line with the trend established in other years.

2.3 MARLAY

The bulk of Marlay's research[2] was devoted to the development of four data bases:

1. Time series data on industrial production for 475 sectors: 413 in manufacturing, 59 in mining, 2 in agriculture, and 1 in construction.

2. Energy consumption data by industry for 1967,

3. Economic output and input data by industry for 1967, and

4. Time series data on energy consumption by the aggregate of manufacturing and mining.

Marlay's work is notable particularly for his time series data on energy consumption for the aggregated manufacturing and mining sector. Because the *Census of Manufactures* and the *Census of Minerals Industries* exclude nonpurchased fuels and petrochemical feedstocks from enumerations of energy consumption, Marlay constructed his own data series on total energy use using data available from the DOE Energy Information Administration (EIA). He reconciled the EIA data at comparable points with the *Census of Manufactures* data series.

Marlay's key results pertain to the period 1972 to 1980. He found that, for manufacturing and mining combined, the energy consumed per dollar of value added declined by 16.5%. Of this amount, 5.9% (equivalent to 35.9% of the change) can be attributed to sectoral shift among the 472 manufacturing and mining sectors. This 35.9% figure is somewhat larger than the estimate of 23.4% for 1975 to 1980 provided by Samuels et al. Indeed, more-recent studies by Marlay,[5,6] in which the results are updated to 1982 and 1984, suggest that up to 50% of the apparent reduction in energy intensity over these longer periods can be attributed to sectoral shift. These results are even more striking in the case of electricity intensity, where 67% of the reduction in the period 1972 to 1984 is due to sectoral shift.

2.4 WERBOS

Werbos recently presented a summary of studies of energy consumption in manufacturing conducted by the EIA.[7] In the EIA work, the manufacturing sector was disaggregated to 18 sectors, and the period 1974 to 1981 was examined. Output data were taken from the U.S. Bureau of Labor Statistics, *Time Series Data for Input-Output Industries*. The data for total energy consumption in the manufacturing sector are indexes of energy use derived from the data in the *Annual Survey of Manufactures* and the *Census of Manufactures*. The data from these documents exclude fuels used as feedstocks and fuels roughly corresponding to captive fuel (i.e., petroleum products diverted from the product stream for fuel use in refineries and chemical plants and metallurgical coal used to make coke).

The results presented by Werbos show that, from 1974 to 1981, there was a 17.2% decline in energy intensity in manufacturing. Of this amount, 5.7% (equivalent to 33.1% of the total decline) can be attributed to sectoral shifts among the 18 manufacturing sectors. This 33.1% figure is remarkably close to the 35.9% figure produced by Marlay for 1972-1980. However, Werbos disaggregated manufacturing only to 18 sectors rather than to the 475 (for manufacturing and mining) examined by Marlay.

Werbos' results are sensitive to his choice of an energy aggregate. In particular, when electricity and fuels are aggregated, the choice of weights is critical. When weighting is done by energy price instead of end-use Btu, Werbos finds that sectoral shift accounts for closer to 50% of the total effect.

2.5 JENNE AND CATTELL

A similar study to ours was done by Jenne and Cattell[8] for manufacturing in the United Kingdom between 1968 and 1978. They used two levels of disaggregation. First, they disaggregated total manufacturing into nine broad categories, then further disaggregated these categories into 104 industries. Their data cover about 90% of all manufacturing in the United Kingdom.

Their results for 1973 to 1978 indicate a 12.5% decline in their measure of energy use per unit of output. Real energy intensity improvements accounted for 5.7% of this decline (equivalent to 45.6% of the change). Of the remaining 6.8% decline, sectoral shift at the nine-category level accounted for 4.2% (equivalent to 33.6% of the change), while sectoral shift among industries *within* the nine categories accounted for 2.6% (equivalent to 20.8% of the total change). Without the disaggregation to the 104-sector level, it would have been presumed that the real energy intensity change was 8.3% (or 66.4% of the total change). Thus, this additional level of disaggregation resulted in a 62% increase (2.6/4.2) in the estimate of the sectoral shift effect.

2.6 SUMMARY AND CONCLUSIONS

An examination of several empirical studies reveals that from one-third to one-half of the reduction in energy intensity in manufacturing from 1972 or 1973 to 1980 or 1981 in the United States can be attributed to shifts in product mix. Indeed, the studies reviewed are in remarkable agreement on this estimate, given the different output and energy aggregates that they employed. However, what is not clear from these studies is the extent of disaggregation of the manufacturing sector needed to observe significant sectoral shift. The levels of disaggregation represented in the four studies vary from two (Myers and Nakamura) to 448 (Samuels et al.). Is it really possible to capture the extent of sectoral shift with two sectors? This idea seems dubious, but it may not be necessary to disaggregate to 448 sectors to capture much of the shift. However, one should not compare the sectoral shift from different analyses with different energy and output measures in order to determine the proper level of disaggregation. The next section presents our preliminary research on this question.

3 HISTORICAL SECTORAL SHIFT IN MANUFACTURING

In this section, the contribution of sectoral shift to observed (i.e., historical) variations in aggregate energy intensity is estimated at alternative levels of disaggregation of the manufacturing sector. The purpose is to enhance understanding of real energy productivity increases, disentangled from shifts in the composition of output. The findings will help answer the question, How much energy intensity change (as indicated by the energy/output ratio over time) is due to real changes in energy use at the microeconomic level and how much to a change in product mix away from energy-intensive products? Also, the extent of disaggregation needed to capture the sectoral shift effect will be determined.

3.1 METHOD OF ANALYSIS

3.1.1 Levels of Disaggregation

The five most energy-intensive manufacturing industries are as follows:

- SIC 26: Paper and allied products,
- SIC 28: Chemicals and allied products,
- SIC 29: Petroleum refining,
- SIC 32: Stone, clay, and glass, and
- SIC 33: Primary metals.

In 1980, these five industry groups accounted for 24% of the gross output in manufacturing and about 80% of the total energy use in manufacturing.[1] The basic notion of the sectoral shift hypothesis is that a major part of the historical decline in manufacturing energy use can be accounted for by a shift of manufacturing output away from *these five* energy-intensive industries. The first level of disaggregation used in this study was thus to two sectors: these five industries and the rest of manufacturing.

The next level of disaggregation was to use the two-digit SIC industry level. There are 20 such sectors (SIC 20-39). The five listed above constitute the materials sector, and the others constitute the nonmaterials sector.* The final level of disaggregation was to break down three of the industries in the materials sector into their component parts, as follows:

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*The nonmaterials industry group mostly produces final goods for consumers and capital goods for business. The materials-intensive industry group mostly produces intermediate products that are sold to other industries.

- SIC 26: Paper and allied products

  - SIC 261, 262, and 263: Pulp and paper mills
  - Other

- SIC 28: Chemicals and allied products

  - SIC 282 and 286: Organic
  - SIC 281, 2873, and 2874: Inorganic
  - Other

- SIC 33: Primary metals

  - SIC 331: Basic steel
  - SIC 3334 and 3353-3355: Aluminum
  - Other

This particular disaggregation is useful because pulp and paper mills and the organic and inorganic chemicals, basic steel, and aluminum industries have higher levels of energy intensity than do the rest of the industries in their same respective two-digit SIC code. The levels of disaggregation used in this report are illustrated in Fig. 1. This disaggregation is not the only one possible. Any shift that affects intensity within a two-digit sector other than SIC 26, 27, or 33 would be incorrectly measured as efficiency changes. Even at the nine-digit product classification level, there could be unidentified product mix changes within diverse industry groups such as chemicals and allied products.

3.1.2 Data Used

The approach used for this analysis was to construct a time series of index numbers reflecting output, energy use, and several measures of energy intensity and sectoral shift. The periods covered were the pre-oil embargo period (1967-1974) and the period 1974-1981. The purpose was to see if and how pre-embargo trends in energy intensity and sectoral shift changed after the embargo.

The data used for the pre-embargo period consisted of a single average rate of growth for each index. No annual data between 1967 and 1974 were used. From 1974 to 1981, annual data on energy use and value added were used. Rates of change were expressed in index number form with 1974 as the base year.

In calculating energy intensities, the measure used for output was census* real value added, deflated by the implicit GNP price deflator (1972 dollars). Energy use was also taken from census data and reflects purchased energy only. The units of measure were British thermal units for fossil fuels and kilowatt-hours for electricity.

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*Referring to data from the U.S. Bureau of the Census, *Census of Manufactures* and *Annual Survey of Manufactures* (various years). For convenience, data from these sources are referred to hereafter simply as census data.

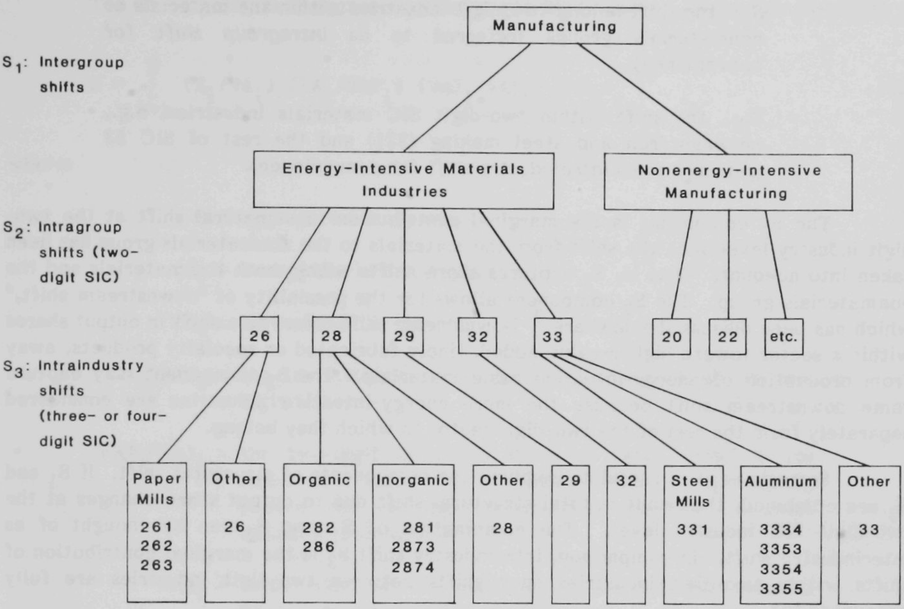

FIGURE 1 Levels of Disaggregation and Types of Sectoral Shift Examined (numbers refer to SIC codes)

3.1.3 Decomposition of Aggregate Energy Intensity

Variations in aggregate energy intensity were decomposed into real improvements in energy productivity at the microeconomic level (measured by real energy intensity) and changes in the composition of output (i.e., sectoral shift). These components were formally defined for the analysis as follows:

- *Real energy intensity*: the (weighted) average of the energy intensities of separate sectors, equivalent to the "real" change in energy intensity that remains when output mix effects are removed from the aggregate measure.

- *Sectoral shift*: the total contribution of changes in output mix to changes in aggregate energy intensity. This index was split into three components:

  - S_1: the shift in shares between the materials and nonmaterials industry groups (referred to as *intergroup shift* for convenience).

- S_2: the shift among two-digit industries within the materials or nonmaterials groups (referred to as *intragroup shift* for convenience).

- S_3: the shift within two-digit SIC materials industries, e.g., between iron and steel making (331) and the rest of SIC 33 (referred to as *intraindustry shift* for convenience).

The S_2 component is the marginal contribution to structural shift at the two-digit industry level once the shift from the materials to the nonmaterials group has been taken into account. That is, S_2 captures share shifts within both the materials and the nonmaterials group. The S_3 component allows for the possibility of "downstream shift," which has been discussed elsewhere.[9] Downstream shift refers to a shift in output shares within a sector toward higher-value-added, finely fabricated or specialty products, away from production of energy-intensive basic materials. The S_3 component may capture some downstream shift because the more energy-intensive industries are considered separately from the rest of the two-digit sector to which they belong.

Sometimes it is useful to combine the components of structural shift. If S_1 and S_2 are combined, the result is total structural shift due to output share changes at the two-digit SIC industry level. The combination of S_1 and S_2 can be thought of as interindustry shift. In comparison, intraindustry shift S_3 is the marginal contribution of shifts within two-digit industries once shifts between two-digit industries are fully accounted for.

The notions of "product shift" and "sectoral shift," as identified by the May 15-16, 1985, meeting of the EMF, essentially differentiate between intra- and interindustry output shifts, respectively, where the industry groupings are either broadly or narrowly defined.

"Technology shift," as has been discussed by EMF, is difficult to capture without detailed process-oriented data; however, aspects of technology shift are embodied in the measure of real energy intensity changes. Real energy intensity change captures all of the changes occurring within each sector, such as (1) improved operations, (2) energy conservation investments, (3) changes in the kinds of processes, e.g., new technology, and (4) changes in the relative use of different processes. An example of the latter would be the shift in steel mills from open-hearth steelmaking using blast furnace metal to electric arc steelmaking using scrap. We do not attempt a decomposition of real energy intensity trends along these lines. The issue has been discussed elsewhere for specific industries.[1]

The recommended approach for decomposition of aggregate energy intensity is the Divisia index.* This index is constructed from growth rates and is superior to simple fixed-weight index numbers. The Divisia index is a popular tool for constructing price indexes in the energy economics field.

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*A decomposition of this type was first done for labor productivity analyses by Myers et al.[10]

The decomposition of aggregate energy intensity relies on the simple identity:

$$E = \sum_{i=1}^{n} (E_i/VA_i)\,(VA_i/VA2_i)\,(VA2_i/VA1_i)\,VA1_i \tag{3}$$

where:

E = aggregate energy use,

E_i = energy use in industry i,

VA_i = value added in industry i,

$VA_i/VA2_i$ = the ith industry's share of value added within its two-digit SIC,

$VA2_i/VA1_i$ = the two-digit industry's share of value added in the respective materials or nonmaterials industry group (where the two-digit industry is the one in which industry i belongs), and

$VA1_i$ = value added in the materials or nonmaterials industry group, whichever industry i falls into.

Industry i is defined at the lowest level of disaggregation. The groupings used to formulate these shares are illustrated in Fig. 1. Dividing Eq. 3 by the value added in manufacturing, VA, yields the basis for our decomposition:

$$E/VA = \sum_{i=1}^{n} (E_i/VA_i)\,(VA_i/VA2_i)\,(VA2_i/VA1_i)\,(VA1_i/VA) \tag{4}$$

By appropriately weighting the changes in the shares of value added (shown in Eq. 4), we derived a measure of the contribution of sectoral shift (changing output mix) to aggregate energy intensity. The remainder is real improvement in energy intensity. The index numbers presented below are multiplicative, e.g., the index for aggregate energy intensity equals the index of sectoral shift times the index of real energy intensity. More detail on the Divisia decomposition is contained in the appendix.

3.2 HISTORICAL TRENDS IN ENERGY INTENSITY

The results obtained from decomposition of the historical data on electricity and fuel intensity are discussed below. Electricity and purchased fossil fuel are treated separately to avoid the problems that can arise when they are aggregated together. Also, the effect of sectoral shift may be different for electricity intensity than for fuel intensity.

3.2.1 Fuel Intensity

Figure 2 presents the indexes of aggregate and real energy intensity over time. Real energy intensity fell approximately 3.3%/yr in the pre-embargo period. This improvement was somewhat offset by a small shift toward energy-intensive manufacturing, causing the aggregate index to show less improvement than it otherwise would have. Part of the reason for this sectoral shift was the strong growth in primary metals in the period 1967-1974. During the 1974-1975 recession, both aggregate and real energy intensity rose sharply, due to a short-run capacity utilization effect. That is, if output falls, but energy use does not fall proportionately, the energy/output ratio rises. This effect is quite pronounced in energy-intensive industries.[9]

During 1974-1981, the sectoral shift caused real energy intensity improvements to be less than the aggregate index would suggest. Also, the trend toward energy-intensive output reversed. The total sectoral shift effect increased by an average of 1%/yr until 1974, when it began to decline. This annual decline (-0.7%) was only slightly less than the average annual increase over the first 7-yr period; thus, the impact of the 1967-1974 shift toward energy intensiveness was nearly eliminated by 1981.

Figure 3 shows the movement of the components that comprise sectoral shift. Almost all of the shift is explained by intergroup shift, S_1. As with the total shift, S_1 rises in the pre-embargo period and generally falls thereafter. The pre-embargo rate of

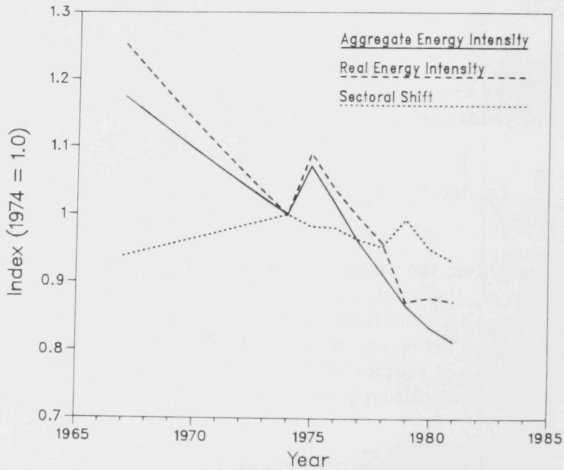

FIGURE 2 Fuel Intensity Decomposition (based on census value added data in 1972 dollars)

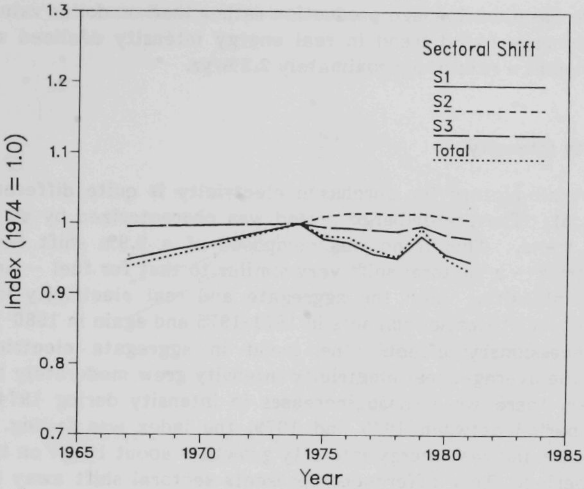

FIGURE 3 Components of Sectoral Shift for Fuel Intensity Decomposition (based on census value added data in 1972 dollars)

change for S_1 was about 0.8%/yr, while the post-embargo rate was an average of -0.7%/yr. However, S_1 rose by more than 3% in 1979 when manufacturing reached its post-embargo peak. This shows that the recovery of materials industries would tend to raise energy intensiveness, had efficiency not been improving.

The intragroup shift, S_2, contributed little to changes in energy intensiveness. Between 1975 and 1979, a gradual 0.3%/yr increase occurred, but was followed by a decline of about 0.5%/yr in 1980 and 1981. Shifts in production within the materials and nonmaterials groups may have occurred, but they contributed little to the aggregate measure of energy intensiveness. Intraindustry shift, S_3, was also small. This is not surprising, since only three industries in our disaggregation scheme (paper, primary metals, and chemicals) contribute to this measure. However, these are industries for which significant downstream shift, i.e., the shift of value added to the advanced stages of processing, have been found in other studies.[10,11] The S_3 trend reverses after the embargo, as does the total sectoral shift. The average growth rate during 1974-1981 was about -0.3%/yr, roughly offsetting S_2.

Returning to the shift-corrected measure of real energy intensity change, it is possible to remove some of the problems of measuring output as value added and thereby derive a measure of efficiency change that is more closely related to changes in physical production. By replacing the value added output measure with an index of physical production for each of the materials industries,[11] we obtain a measure of real energy intensity change based on tonnage production rather than on dollar value production (see Fig. 4). The tonnage-based trend in real energy intensity declined steadily over the entire time period at a rate of approximately 2.2%/yr.

3.2.2 Electricity Intensity

The overall picture for purchased electricity is quite different from that for fuels (see Fig. 5). The pre-embargo period was characterized by an aggregate 2%/yr electrification trend. This trend was composed of a 0.9% shift toward electricity-intensive industries -- a sectoral shift very similar to that for fuel -- and a 1.1% change in real energy intensity. Both the aggregate and real electricity intensities exhibit pronounced capacity utilization impacts in 1974-1975 and again in 1980-1981. Because of these large recessionary effects, the trend in aggregate electricity intensity is uncertain. On the average, real electricity intensity grew moderately between 1974 and 1981. However, there were sharp increases in intensity during 1974-1975 and 1980-1981. In the period between 1975 and 1979, the index was falling. The difference between aggregate and real energy intensity growth is about 1%/yr on the average in the post-embargo period. This difference represents sectoral shift away from electricity-intensive industries, a marked reversal of the pre-embargo trend. Again, the shift effect is similar to that for fuel.

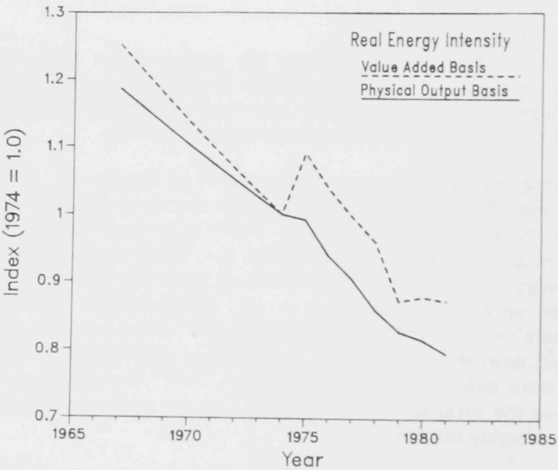

FIGURE 4 Effect of a Ton versus Dollar Value Measure of Output on Fuel Intensity Decomposition (based on 1972 dollars)

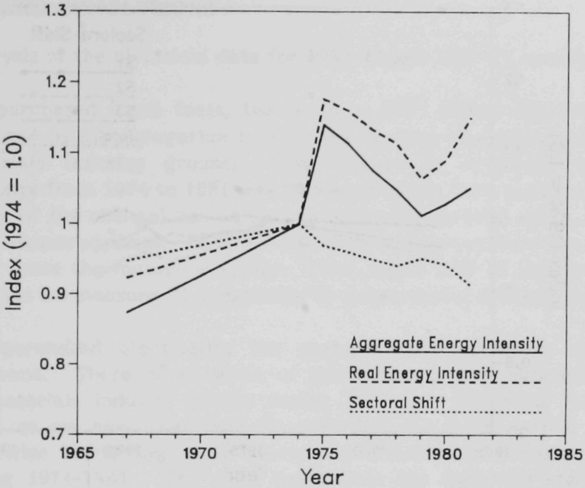

FIGURE 5 Electricity Intensity Decomposition (based on census value added data in 1972 dollars)

The general pattern of movement of the components of sectoral shift in relation to electricity intensity is similar to that for fuel intensity (see Fig. 6). During the pre-embargo period, the intergroup shift, S_1, comprises most of the sectoral shift, growing at slightly more than 0.5%/yr. Intragroup shift, S_2, and intraindustry shift, S_3, are small. In the post-embargo period, however, the S_1 and S_2 shifts each contribute an average of -0.5%/yr to the total sectoral shift. As in the fuel intensity case, the 1979 recovery was a force in the direction of an increase in energy intensity, due to shifts from the nonmaterials to the materials industries.

When a physical output index is used to measure materials industry output, a larger pre-embargo electrification trend is revealed than when a dollar value index is used (see Fig. 7). The electricity data, however, show capacity utilization effects in both 1975 and 1980-1981, while the corresponding fuel data do not. This suggests that real electricity intensity (i.e., of physical output) is affected by economic downturns. In the short run, electricity-using capital equipment may be less flexible than fossil-fuel-using capital equipment; that is, for example, pumps, fans, and conveyors may continue to be run in low production situations.

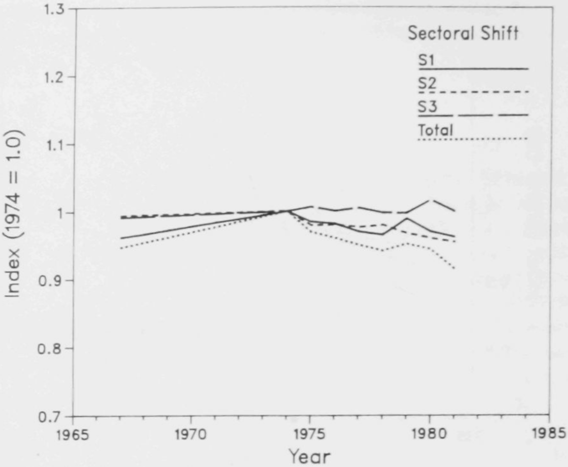

FIGURE 6 Components of Sectoral Shift for Electricity Intensity Decomposition (based on census value added data in 1972 dollars)

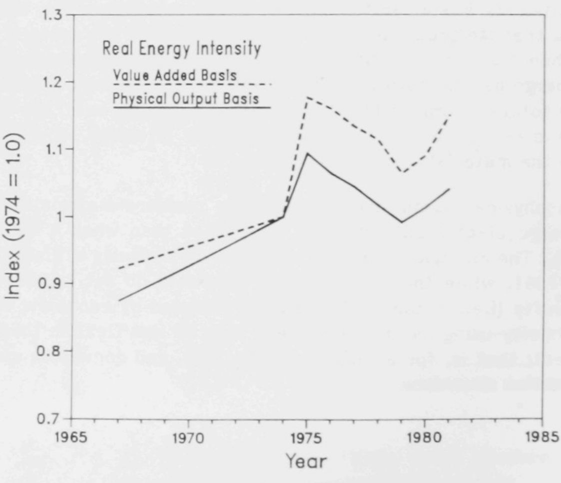

FIGURE 7 Effect of a Ton versus Dollar Value Measure of Output for Electricity Intensity Decomposition (based on 1972 dollars)

3.3 SUMMARY AND CONCLUSIONS

Our analysis of the historical data for 1967-74 and 1974-81 reveals the following:

- For purchased fossil fuels, the sectoral shift effect essentially is captured by disaggregation to only two sectors (materials and nonmaterials industry groups). The change in aggregate energy intensity from 1974 to 1981 was 20.5%, of which 7.0% (equivalent to 34.1% of the change) can be accounted for by sectoral shifts, as we have measured them. Of this 7.0%, 5.6% can be attributed to shifts away from the materials sector. Thus, about 80% of this sectoral shift (as we measure it) is captured by a two-sector disaggregation.

- For purchased electricity, the sectoral shift effect is slightly different. There is evidence of shifts *among* the materials and nonmaterials industry groups during 1974-81. The *total* sectoral shift, as we have measured it, contributed a 9.0% decline in an otherwise rising aggregate electricity intensity in manufacturing during 1974-1981. The shift away from the materials industries accounted for a decline in aggregate electricity intensity of 4.0%, and the shifts among the two-digit materials and nonmaterials industries accounted for another 4.8% decline in aggregate electricity intensity. Also, real electricity intensity in manufacturing as a whole increased somewhat during 1974-1981.

- The change in sectoral shift trends before and after the embargo is large. In particular, the share of total output attributable to energy-intensive industries increased before the embargo, but declined afterwards. For both fuels and electricity, the net change in the post-embargo sectoral shift rate was about -2%/yr.

Another conclusion is that it is necessary to examine purchased fossil fuels and electricity separately because the historical trends differ and because different levels of disaggregation are needed to capture sectoral shift. Our preliminary conclusion, however, is that disaggregation beyond the two-digit SIC code level may not be necessary to capture the major post-1974 sectoral shift effects.

4 DECOMPOSITION OF THE WHARTON PROJECTIONS

This section presents an analysis of the Wharton macroeconomic industrial output series for sectoral shift. These data include both the historical data, provided by EIA, that Wharton uses to make its projections, as well as Wharton's projections to 1994. These projections are not identical to those used in the EMF-8 study, but they contain the same essential features. The purpose of our analysis is to determine if the historical data used by Wharton show a sectoral shift similar to that determined in Sec. 3 (at the level of aggregation available in their data), and how much sectoral shift is part of the Wharton forecasts. To do this, we decompose the Wharton historical data, which consist of constant-dollar value added and purchased energy use at the two-digit SIC level. We also compute projected sectoral shift, assuming no change in energy intensity after 1981.* It is not possible to compute intraindustry shift (S_3), since the Wharton data are not available at the level of disaggregation we have chosen to represent that phenomenon. However, both inter- and intragroup shifts (S_1 and S_2, respectively) are computed.

4.1 FUEL INTENSITY

The basic trends derived from Wharton's historical data are similar to those obtained using our deflated census value added measure of output: real fuel intensity generally falls both before and after the embargo, and sectoral shift rises before the embargo and falls thereafter (see Fig. 8). Much of the decline in real energy intensity occurs after 1971. On the other hand, no sectoral shift occurs during the 1971-1974 period, but the Wharton projections show continued sectoral shift after then. The average decline is about 0.5%/yr during 1985-1994, in contrast to the 1%/yr decline during 1974-1985.

The components of sectoral shift show similar movement regardless of whether the Wharton data (see Fig. 9) or our deflated value added data are used as the measure of output. Historically, most of the sectoral shift is explained by intergroup shift, S_1. The intragroup shift, S_2, shows no apparent pattern or trend. However, in the projections, a slight gap appears between S_1 and total sectoral shift, suggesting that S_2-type shifts will increase in the future. This trend begins in 1981, the last year of the energy data, so it is impossible to say how more-recent changes in sectoral energy intensity have affected this index.

4.2 ELECTRICITY INTENSITY

The general trend obtained for electricity intensity from the Wharton data (see Fig. 10) is similar to the one obtained when census value added data are used to measure output. Real energy intensity rises before 1974 but fluctuates widely thereafter. Sectoral shift contributes to electrification before the embargo and to improved (aggregate) energy intensity afterwards. However, the values obtained for real energy

*This is the last year for which energy data were available to us.

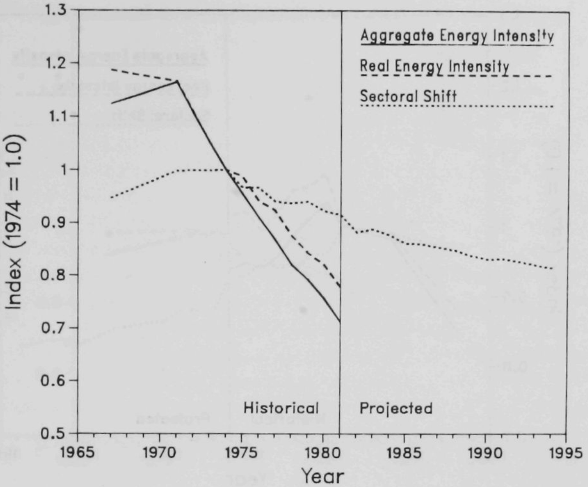

FIGURE 8 Wharton Output Data on Fuel Intensity Decomposition (based on 1972 dollars)

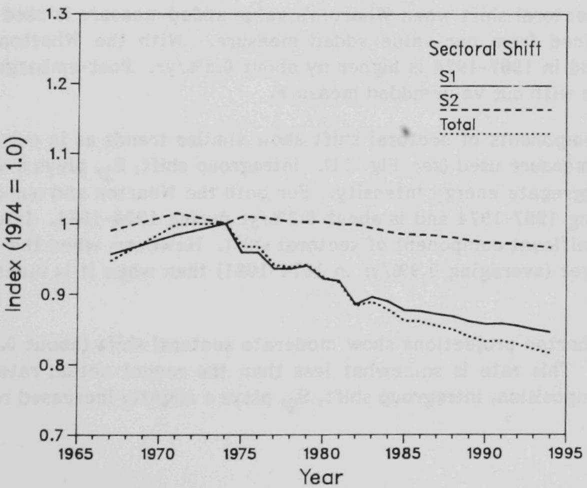

FIGURE 9 Wharton Output Data on the Components of Sectoral Shift for Fuel Intensity Decomposition (based on 1972 dollars)

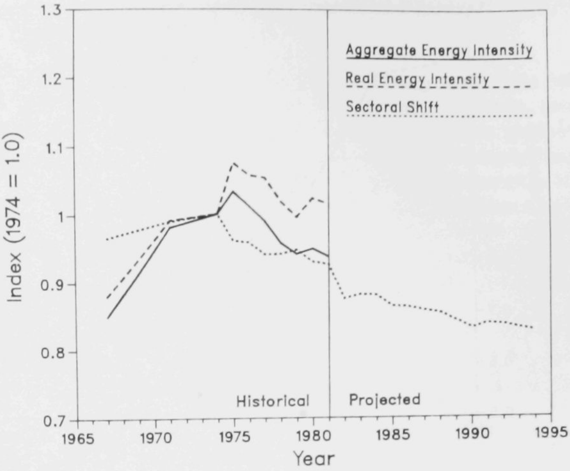

FIGURE 10 Wharton Output Data on Electricity Intensity Decomposition (based on 1972 dollars)

intensity and sectoral shift when Wharton's value added measure is used are not identical to those obtained from our value added measure. With the Wharton data, the electrification trend in 1967-1974 is higher by about 0.5%/yr. Post-embargo sectoral shift is about the same with our value added measure.

The components of sectoral shift show similar trends as in our study, regardless of the output measure used (see Fig. 11). Intragroup shift, S_2, plays a very small role in determining aggregate energy intensity. For both the Wharton and our census data, S_2 is near zero during 1967-1974 and is about 0.3%/yr during 1974-1981. Intergroup shift, S_1, is the most significant component of sectoral shift. However, when the Wharton data are used, S_1 is larger (averaging 0.9%/yr in 1974-1981) than when it is measured with census data (0.5%/yr).

The Wharton projections show moderate sectoral shift (about 0.5%/yr) occurring in the future. This rate is somewhat less than the recent actual rate. As in the fuel intensity decomposition, intragroup shift, S_2, plays a slightly increased role in the future.

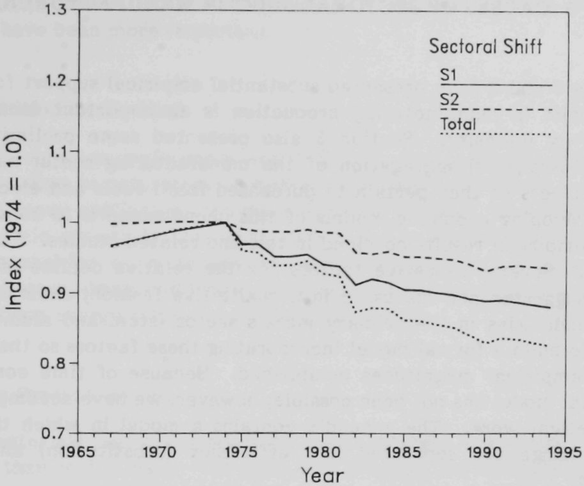

FIGURE 11 Wharton Output Data on the Components of Sectoral Shift for Electricity Intensity Decomposition (based on 1972 dollars)

5 CAUSES OF SECTORAL SHIFT IN MANUFACTURING

Sections 2 and 3 have presented substantial empirical support for the hypothesis that sectoral shift in manufacturing production is an important factor in explaining changes in energy intensity. Section 3 also presented some preliminary conclusions regarding the levels of disaggregation of the manufacturing sector needed to capture sectoral shift effects as they pertain to purchased fossil fuels and electricity use. The next step in developing economic models of this phenomenon is to consider the possible causes for the empirical results obtained in this and related studies. That is the purpose of this section. Several causative factors for the relative decline of basic materials industries are suggested and discussed in a qualitative fashion; examples are presented regarding two industries in the primary metals sector (steel and aluminum). The next step would be to build a formal model incorporating these factors so that hypotheses can be tested and empirical magnitudes established. Because of time constraints, a fully developed formal model has not been possible; however, we have accomplished some preliminary theoretical work. The appendix contains a model in which the effects of an energy price change are separated into efficiency (substitution) and sectoral shift (output) effects.

5.1 GENERAL CAUSES

The main causes of sectoral shift in manufacturing production fall into five basic categories:

- The differential impacts of rising relative energy prices on costs and, hence, output prices,
- Trends in consumer demand for manufactured products (e.g., differentials in income effects),
- Trends in technology (the design and manufacture of products),
- Changes in the inputs used to manufacture products, and
- International trade patterns.

These categories are discussed below. The discussion follows substantially the work of Ross, Larson, and Williams.[12]

5.1.1 Price Changes

Rising relative energy prices tend to increase production costs most in the sectors with the greatest energy intensities. As these costs are passed along to customers through price increases, demand shifts away from energy-intensive products. (The model in the appendix permits analysis of this effect.) While such an effect is plausible in theory, the extent to which sectoral shift can be accounted for by energy price increases is uncertain. Other causes of the sectoral shift over the past 10 years may turn out to have been more important.

5.1.2 Changes in Product Demand

Affluent consumer preferences are shifting to less-materials-intensive products, a trend that is leading to saturation in markets for bulk materials (e.g., sheet steel for automobiles and heavy appliances) and growth in new markets for value-added-intensive products. Economic growth is now being dominated by high-technology products with generally low intensities of materials use, such as solid-state electronics, computer hardware and software, drugs and biogenetics, and telecommunications. The result is to add to the shift from energy-intensive materials industries.

5.1.3 Changes in Product Design

Many materials being supplied to bulk markets are being used far more efficiently now than in the past -- in part as a strategy for mitigating the impacts of increased costs, especially energy costs, and in part as a response to competitive pressures from substitutes with more-desirable properties. This competition from substitutes has encouraged technological advances in the design of traditional materials, leading, for example, to higher strength-to-weight ratios or increased durability. Such advances permit the same services to be provided with lower levels of material input, resulting in lower levels of output from the energy-intensive manufacturing sectors.

5.1.4 Shifts in International Trade

Since 1980, the pattern of U.S. trade in materials has been shifting. Manufacturing is beginning to move to less-developed countries (LDCs) and resource-rich countries, particularly for the most basic upstream products (i.e., those manufactured in the first levels of processing within each materials industry). The net result is that production in the United States is growing slower than demand.

Many upstream products, such as steel in rough shapes, pulp and products such as linerboard (for the facing of shipping containers), industrial chemicals immediately derived from ethylene, and primary aluminum, have already become international commodities. The advantages offered by foreign producers for these and other upstream products include low prices for hard-to-transport inputs and low labor costs. Improvements in shipping, especially the use of larger ships and the modernization of ports and materials-handling facilities, have also substantially reduced costs. In addition, the character of these products as international commodities has been enhanced by the decreasing concentration of ownership of production facilities. Many new companies have come into being in the steel and aluminum industries and are being created in the petrochemicals industry; LDC government ownership is also common.

In the future, it is likely that U.S. producers will gradually yield certain upstream products to foreign plants, while trying to secure a market share in (1) less-capital-intensive downstream finishing and fabrication operations and (2) secondary industries, which are based on recycled materials. A sizable potential for growth exists in sophisticated materials such as high-strength steels, corrosion-resistant steels, composites, and plastic-aluminum laminates. For these downstream products, U.S. producers have the advantage of being close to markets (although this does not guarantee dominance in these new product areas).

Manufacture based on recycled materials is also of growing importance in the United States. Examples of recycled materials include aluminum (especially recycled beverage cans), steel, paper, and plastic. Recycling has long been important for relatively costly metals such as copper. The energy savings are, in some cases, substantial. For example, making secondary aluminum requires only 5-10% as much energy as primary aluminum. Steel products made from scrap typically require about 50% as much energy as those made from iron ore.

5.2 EXAMPLES

5.2.1 Steel

All the factors mentioned above that contribute to the declining relative role of materials production in the U.S. economy can be illustrated with steel. Factors contributing to the saturation, if not decline, in per capita steel consumption include maturing markets, rising substitution by lighter materials, and production of new steels with higher strength-to-weight ratios and better durability characteristics.

The automotive market, which accounted for 15-20% by weight of all steel industry shipments over the last decade, has tightened severely, reducing the demand for steel. The number of automobiles per person in the United States has leveled off in recent years at about one for every two persons, and average ownership periods have lengthened (i.e., from 5.5-6.0 yr before 1975 to 7.4 yr in 1983). As a result, new car sales are not expected to rise much beyond 1975-1978 levels through 1990.[13] The net function of production today is to replace old cars.

Since the mid-1970s, minimum automotive fuel economy standards have forced a general downsizing of automobiles and increased substitution of lighter materials for traditional ones. The weight of the steel in the average U.S.-made car dropped from 1139 kg to 802 kg between 1975 and 1978 and is projected to drop to 625 kg by 1992.[14] To compete against makers of aluminum, plastics, fiberglass, and other high-strength, lightweight materials usable in vehicles, the steel industry has increased production of more-sophisticated steels, such as those with higher strength-to-weight ratios or that have been galvanized or coated for rust prevention. The fraction of high-strength and stainless steels in the average car has risen from 5% in 1975 to 13.5% in 1978 and is expected to rise well over 20% by 1992.[13]

New markets for steel exist, but they are largely for special applications involving high-value-added products (e.g., electronic equipment, medical technology). The general trend in the United States is of growth in less-steel-intensive products.

Stagnant domestic demand has helped create the major problem of the U.S. steel industry: antiquated capital. The last greenfield, or all new, integrated mill was built in the 1960s. Building a greenfield mill would not be profitable because the increase in capital carrying charges would exceed the reduction in operating cost. Some modernization of existing mills, however, has been cost-effective. For example, basic-oxygen shops have replaced open hearth steel furnaces, continuous casters have replaced batch casting of ingots, and large blast furnaces have replaced some small old furnaces with low capacity. However, such modernization has proceeded more slowly in the United States than in other countries such as Japan.

In many other countries, steel production costs are lower than in the United States,[15] strikingly so, for example, in South Korea. In certain areas, such as in East Asia, plant construction is cheaper. In countries where the creation of basic manufacturing facilities is a priority of the government, the cost of capital (i.e., the effective interest rate) may be lower. Labor costs are also lower in many countries. Ore costs for mills at many deep-water ports are lower than the U.S. average, more than compensating for the U.S. advantage in coal costs.[16] In addition, some foreign operations, e.g., those at antiquated European mills, are directly subsidized.[15] These advantages and the high overseas buying power of the dollar (about one-third above 1970s rates in Europe and Japan) more than make up for the added transportation costs in shipping foreign-made steel to the United States.

These reasons help explain the relative decline of the U.S. steel industry, which has contributed to the sectoral shift away from basic materials industries. Few of the options open to the industry seem likely to be adopted on a scale sufficient to reverse this trend. Such options include:

1. Continuing to import rough-shaped steel but modernizing shaping and finishing facilities in the United States,

2. Entering joint ventures with Japanese firms in order to acquire technical expertise and technically oriented capital,

3. Developing the means for the secondary steel industry (minimills) to use inputs other than scrap, such as direct-reduced or sponge iron, or to produce high-quality products out of steel containing copper or other impurities (as is characteristic of scrap). This portion of the industry has been robust, growing at 10%/yr until 1981, and producing 18% of U.S. steel in 1983. However, future growth is limited by the small range of products that can be made from scrap.

The energy use impacts of such options are uncertain, but could be assessed theoretically if a formal model of energy demand in manufacturing could be developed along the lines proposed in this paper.

5.2.2 Aluminum

Another example of the causes of sector shift affecting the primary metals sector is aluminum. The use of aluminum in the United States grew rapidly as steel consumption approached saturation levels in the 1940s, 1950s, and 1960s, reflecting the increasing use of aluminum as a substitute for steel and other heavier materials. However, the consumption per dollar of GNP began to decline in the early 1970s, a trend that has been accelerating in the 1980s. Per-capita demand appears to have leveled off in the late 1970s.

Substitution by other materials does not substantially affect aluminum consumption, as aluminum is already one of the most desirable materials for many applications requiring strength, stiffness, lightness, and durability. However, maturing markets and more-efficient use of material in existing applications are both contributing to a saturation of demand.[13]

An examination of specific markets shows only packaging and transportation growing faster than GNP in the 1970s, and only packaging in the 1980s.[17] Other materials are competing fiercely with aluminum in both of these markets. The largest single market for aluminum is containers and packaging, accounting for about 30% of all U.S. shipments in 1981. Aluminum cans, which accounted for 80% of this market, first became available to consumers in the early 1960s. By 1981, they accounted for nearly 90% of all beverage cans.

In transportation, aluminum use dropped in the early 1980s, although the transportation market has maintained a 15-20% share of all aluminum use. Declining absolute use can be attributed in part to slowed growth of the automobile aluminum market.

At the same time that markets are maturing, reductions are continuing to be made in the material intensity of specific products. A good example is beverage cans. Since 1965, thinner side walls have led to a 22% reduction in total weight, while the introduction of necking at the top of cans (among other changes) has reduced material requirements for the heavier, more expensive alloy used in the lids by about 13%.

Primary aluminum production in the United States is expected to decline with respect to domestic consumption for two reasons: (1) secondary production, which grew from 25% to 50% of primary production between 1970 and 1983, will continue growing rapidly,[17] and (2) imports of primary aluminum are expected to increase.

Aluminum smelters are being built in Australia, Canada, and Brazil where new power plants can supply power at under 2¢/kWh.[18] Energy sources are remote surface coal in Australia and hydropower in both Canada and Brazil. Unexploited natural gas is also a source of cheap electricity for new smelting capacity. Existing smelters in many areas outside the United States receive energy at prices even lower than 2¢/kWh. Meanwhile, in the United States, the price of electricity to smelters is above 2¢/kWh (some regional prices are 2.5¢/kWh in the Ohio Valley, 2.7¢/kWh in the Pacific Northwest, and 3.7¢/kWh in the Tennessee Value Authority area) and is moving sharply upward. Each 1¢/kWh price increase roughly corresponds to a 10% increase in the cost of producing primary aluminum. In the Gulf states, where 17% of the aluminum capacity is located, some smelters have already been closed as a result.

The future outlook is for imports to continue to increase while domestic smelting capacity is reduced on a regional basis, and for U.S. aluminum firms to turn towards foreign projects, increase production of secondary aluminum (e.g., recycling of aluminum cans), and upgrade domestic finishing operations.

6 SUMMARY AND CONCLUSIONS

As discussed earlier in this paper, the development of economic models for applied fields such as energy economics typically proceeds through several stages. The first two of these stages, the accumulation and examination of data to determine the salient facts of manufacturing energy demand, have been covered in Secs. 1-4. Focus has been on differentiating the effects of energy productivity increases and changes in product mix on aggregate energy intensity. One hypothesis examined is that sectoral shift away from energy-intensive materials production has played a significant role in the decline in manufacturing energy demand since the 1974 OPEC oil embargo.

The main results of the analysis are as follows (see Table 3):

- Real fuel intensities were, on the average, falling rapidly before the 1974 oil embargo. The rate of decline increased after the embargo.

- Real electricity intensities were, on the average, rising rapidly before the embargo. The rate of change has been mixed since then. The reason is that electrification is still increasing, because of such new production technologies as computer controls and specific electromagnetic heating, while electricity conservation, through such measures as efficient lamps, furnaces, and motors, is also being implemented.

TABLE 3 Trends in Real Energy Intensity and Sectoral Shift before and after the 1974 Oil Embargo (%/yr change)

Trend Indicators	Fuel Use	Electricity Use
Real energy intensity[a]		
Pre-embargo	-1.9	+2.0
Post-embargo	-2.9	~0[b]
Difference	-1.0	<0[b]
Sectoral shift impact		
Pre-embargo	+0.9	+0.8
Post-embargo	-1.0	-1.3
Difference	-1.9	-2.1

[a]Calculated using tons (rather than dollar value) as the measure of output.

[b]No clear trend is apparent.

- Production shares in energy-intensive sectors shifted dramatically toward lower-energy-intensity products after the embargo. This shift is epitomized by the relative contraction of the primary metals sectors and the relative expansion of such sectors as printing and publishing, office and computing machines, communication and electronic equipment, and instrumentation.

- Both before and after the embargo, the impact of sectoral shift has been similar for fuel use and electricity use. After the embargo, the impact of sectoral shift in both cases changed in the same direction, reducing the overall ratio of energy consumption to production in manufacturing.

- The effect of sectoral shifts on aggregate energy intensity is almost completely described by the shifts in production from energy-intensive sectors (as a whole) to the rest of manufacturing.

- The Wharton projection series shows slightly less sectoral shift than what has already occurred in the post-embargo period. This is true for both fuel and electricity intensity.

In Sec. 5, the causes of the observed sectoral shift have been postulated. These causes include:

- Changes in energy price,

- Saturation, at high income levels, of demand for materials-intensive final products,

- Improvements in materials efficiency, resulting in a need for fewer materials used per unit of product or service, and

- A shift in international trade patterns since 1980, resulting in increased production of energy-intensive, upstream materials overseas and in relatively more production of value added goods within the United States.

These causes need to be analyzed by a formal model based on empirical data if their relative contributions are to be assessed. Such a model would improve understanding of industrial energy demand forecasts, by linking those forecasts directly to the underlying causes of sectoral shift, which is a large determinant of energy demand.

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APPENDIX: DIVISIA DECOMPOSITION OF ENERGY INTENSITY

A.1 DERIVATION

With E_i and Q_i denoted as energy use and output in sector i, respectively, and with E and Q as their respective sums over all sectors, s_i is the output share of sector i:

$$e = \frac{E}{Q} = \frac{\sum E_i}{\sum Q_i} \tag{A.1}$$

$$= \frac{\sum (E_i/Q_i) \cdot Q_i}{\sum Q_i}$$

$$= \sum (E_i/Q_i) \cdot (Q_i / \sum Q_i)$$

$$= \sum e_i \cdot s_i .$$

Differentiating Eq. A.1 over time, t, yields

$$\frac{de}{dt} \cdot \frac{1}{e} = \sum \frac{de_i}{dt}\left(\frac{s_i}{\sum e_i s_i}\right) + \sum \frac{ds_i}{dt}\left(\frac{e_i}{\sum e_i s_i}\right) \tag{A.2}$$

or

$$\frac{d\ \ell n(e)}{dt} = \sum \frac{d\ \ell n(e_i)}{dt} \ \frac{e_i s_i}{\sum e_i s_i} + \sum \frac{d\ \ell n(s_i)}{dt} \ \frac{e_i s_i}{\sum e_i s_i} \tag{A.3}$$

Integrating Eq. A.3 gives the Divisia decomposition

$$\ln\left[\frac{e(t)}{e(t-1)}\right] = \int_{t-1}^{t} \sum w_i \frac{d\ \ell n(e_i)}{dt}\, dt + \int_{t-1}^{t} \sum w_i \frac{d\ \ell n(s_i)}{dt}\, dt . \tag{A.4}$$

Finally,

$$w_i = \frac{e_i s_i}{\sum e_i s_i} = \frac{(E_i/Q_i)\ (Q_i/Q)}{\sum\ (e_i/Q_i)\ (Q_i/Q)} \tag{A.5}$$

$$= \frac{(E_i/Q)}{\sum\ (E_i/Q)}$$

$$= \frac{E_i}{\sum\ E_i},$$

so that the weights in Eq. A.4 are energy shares.

A.2 THEORETICAL INTERPRETATION

The decomposition formula above has a convenient interpretation that is related to the standard economic theory of the derived demand for inputs. While it is widely recognized that the sectoral shift component is related to an "output effect" and the energy efficiency component is related to a "substitution effect," we are not aware of a formal statement of these relationships. We feel that the theoretical model outlined here could serve as a basis for future research.

In this model we assume that there are only two inputs in each manufacturing industry: energy and everything else (aggregated in some way). While this assumption is unrealistic (and can be relaxed with modest effort), it permits us to focus on the key issues. The standard conclusion of the theory of derived demand is that

$$\frac{\partial\ \ell n\ E_i}{\partial\ \ell n\ P_e} = \varepsilon^i_{ee} = S_{ei}\ N^D_i + (1 - S_{ei})\ \sigma_i, \tag{A.6}$$

where:

E_i = energy demand in manufacturing sector i,

P_e = price of energy,

ε^i_{ee} = own-price elasticity of demand for energy in i,

S_{ei} = share of energy inputs in sector i,

N_i^D = elasticity of demand for the output of sector i, and

σ_i = elasticity of substitution of energy for other inputs in i.

To convert to energy intensity, we note that

$$\ln (E_i/Q_i) = \ln e_i = \ln E_i - \ln Q_i , \tag{A.7}$$

where:

Q_i = output of sector i and

$e_i = E_i/Q_i$.

This implies that

$$\begin{aligned} \frac{\partial \ln e_i}{\partial \ln P_e} &= \frac{\partial \ln E_i}{\partial \ln P_e} - \frac{\partial \ln Q_i}{\partial \ln P_e} \\ &= \varepsilon_{ee}^{i} - S_{ei} N_i^D \\ &= (1 - S_{ei}) \sigma_i . \end{aligned} \tag{A.8}$$

This result follows because

$$\begin{aligned} \partial \ln Q_i / \partial \ln P_e &= \frac{\partial \ln Q_i}{\partial \ln P_i} \frac{\partial \ln P_i}{\partial \ln P_e} \\ &= N_i^D S_{ei} , \end{aligned} \tag{A.9}$$

where P_i is the price of output in sector i.

Next, we examine how the output shares S_i respond to changes in the price of energy. Define $S_i = Q_i/Q$, where Q is total output in manufacturing. Then,

$$\partial S_i = \frac{\partial Q_i Q - Q_i \sum_{j=1}^{n} \partial Q_j}{Q^2} \text{ , or}$$

$$\frac{\partial S_i}{S_i} = \frac{Q}{Q_i} \left(\frac{\partial Q_i Q - Q_i \sum_{j=1}^{n} \partial Q_j}{Q^2} \right)$$

$$= \frac{\partial Q_i}{Q_i} - \frac{\sum_{j=1}^{n} \partial Q_j}{Q} \tag{A.10}$$

$$= \frac{\partial Q_i}{Q_i} - \sum_{j=1}^{n} \frac{\partial Q_j}{Q_j} \frac{Q_j}{Q}$$

$$= \frac{\partial Q_i}{Q_i} - \sum_{j=1}^{n} \frac{\partial Q_j}{Q_j} S_j .$$

Here sector i is included in j = 1, . . ., n.

Thus,

$$\partial \ln S_i = \partial \ln Q_i - \sum_{j=1}^{n} S_j \, \partial \ln Q_j . \tag{A.11}$$

For a change in the price of energy, we have

$$\frac{\partial \ln S_i}{\partial \ln P_e} = S_{ei} \, N_i^D - \sum_{j=1}^{n} S_i \, S_{ei} \, N_j^D . \tag{A.12}$$

The expressions for $(\partial \ln e_i)/(\partial \ln P_e)$ and $(\partial \ln S_i)/(\partial \ln P_e)$ can be substituted into the Divisia decomposition formula above (Eq. A.4). Note that $(\partial \ln e_i/\partial \ln P_e)$ depends only upon the elasticity of the substitution term (and S_{ei}, the share of energy), and that $(\partial \ln S_i)/(\partial \ln P_e)$ depends only upon demand elasticities (and the S_i and S_{ej} terms). Hence, the Divisia decomposition separates output effects from input substitution effects resulting from a change in the price of energy.